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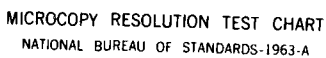
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**AUTOMATIC RECOGNITION OF  
MESOCYCLONES FROM SINGLE DOPPLER  
RADAR DATA**

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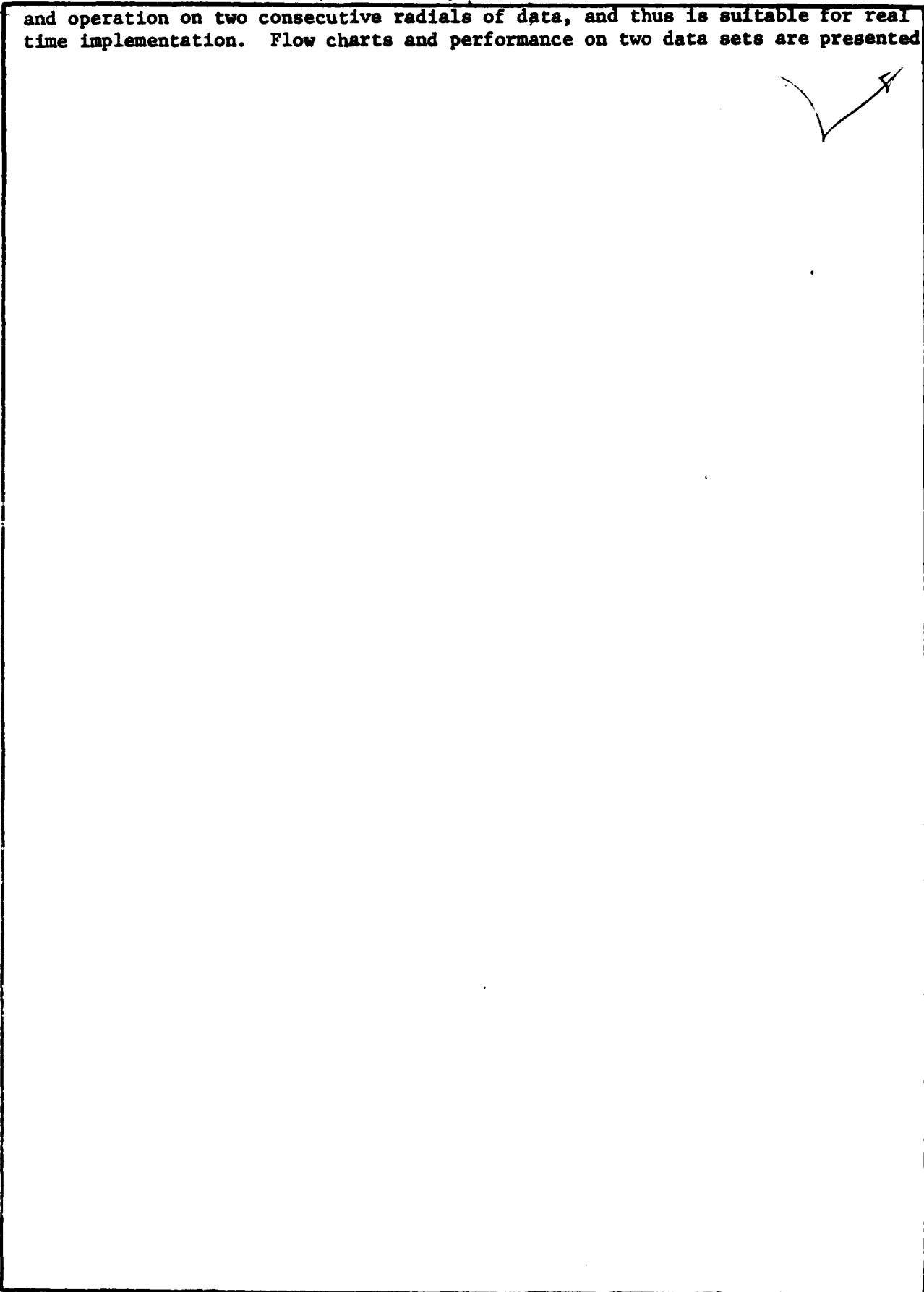
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and operation on two consecutive radials of data, and thus is suitable for real time implementation. Flow charts and performance on two data sets are presented.



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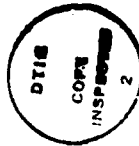
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## 1. INTRODUCTION

Doppler radar is capable of making accurate estimates of the radial component of velocities within severe thunderstorms. A trained observer can examine a field of radial velocities and recognize the characteristic signature of various flow patterns. Donaldson (1970) stipulated criteria whereby a vortex can be identified from single Doppler-radar observations. Briefly, there must be a localized region of persistently high ( $\geq 5 \times 10^{-3} \text{ s}^{-1}$ ) azimuthal shear (i.e., the velocity gradient along an arc at constant range) which has a vertical extent equal or longer than its diameter. These criteria were further refined by Burgess *et al.* (1979) who used them successfully to detect mesocyclones and inform the National Weather Service and the USAF Air Weather Service of severe thunderstorm potential. The manual process consists of recognizing circulation patterns, confirming height and time continuity of the patterns, and verifying that the radial velocity shear across the circulation is larger than a range dependent threshold value. This report concentrates on the automatic recognition of circulation patterns from Doppler velocity fields. Confirmation of height and time continuity is not considered; however, identification of large shear is an inherent part of the technique and is discussed in detail.

## 2. THE MESOCYCLONE

It has been known for some time that a cyclonic circulation larger than the tornado may exist in thunderstorms (Brooks, 1949). The larger rotation precedes the tornado and acts as a vorticity producing source. Fujita (1963) labeled this structure the mesocyclone, noting that its diameter is too small to be observed with conventional surface weather observations. Previous Doppler studies have shown that single Doppler radar can easily detect and track mesocyclones (Donaldson, 1970; and Burgess, 1976). From Doppler data, the average mesocyclone is known to last for over an hour with a rotational velocity of  $23 \text{ m} \cdot \text{s}^{-1}$ ; a core diameter of 5 km; and a vertical extent of 8 km [further characteristics are contained in Burgess *et al.* (1982)].

The flow in a mesocyclone theoretically can be modeled as a Rankine combined vortex, characterized by two flow regimes. The Doppler velocity field mapped by an idealized Doppler radar (perfect resolution) is depicted in Figure 1. The inner region is the vortex core where velocity is proportional to radius at all radii out to the radius of maximum tangential velocity (solid body rotation). The outer regime, outside of the core, features velocities which decrease with

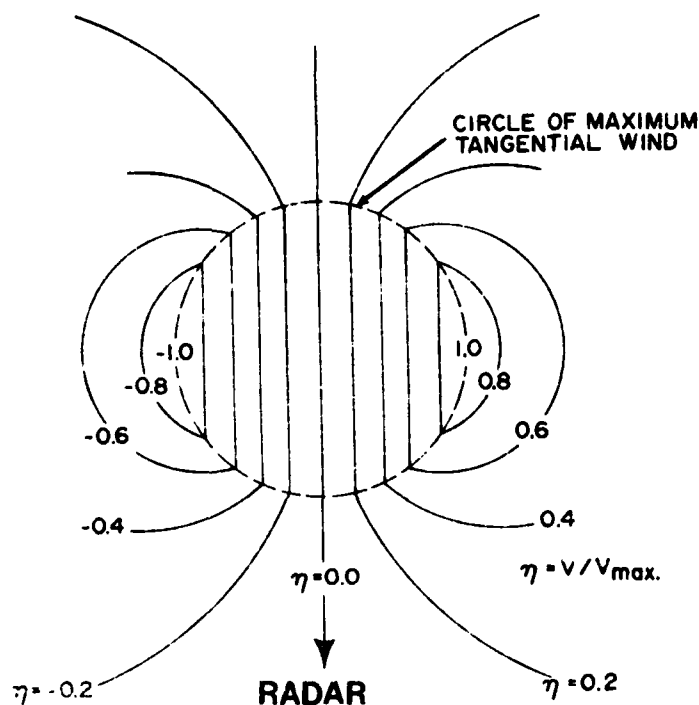


Figure 1. Single Doppler velocity pattern of a distant and stationary cyclonic vortex as seen by a Doppler radar scanning with infinite resolution at low elevation angle.

the inverse of radius (potential vortex). The outer potential vortex gradually merges with and becomes indistinguishable from the ambient flow. Total mesocyclone diameter (including the potential vortex portion) deduced from surface and multiple-Doppler data, is about three times the core diameter.

### 3. PATTERN RECOGNITION TECHNIQUES

Many schemes for recognizing two dimensional patterns have been utilized in various fields of science. These can be grouped into the following three distinct categories: 1) distance measure techniques which compare ground truth (or model) to data and minimize a suitable measure of deviation between the two; 2) correlation techniques

that maximize the correlation coefficient between the model pattern and data; and 3) pattern recognition techniques which classify data according to a set of attributes.

Distance measure techniques require a suitable definition of a distance between a true pattern vector and the data. The magnitude of this distance is then compared to a set of thresholds which are boundaries of decision regions. Two distances have been considered:

The Euclidean distance

$$d_e = |\vec{x} - \vec{m}| \quad (1)$$

where  $\vec{x}$  is the data vector and  $\vec{m}$  the true, or model, vector (Tou and Gonzales, 1974). For instance,  $\vec{m}$  could consist of an array of velocities normalized to the maximum (or to the rms value). As an example, nine Doppler velocities, from three consecutive azimuths and three consecutive ranges, of an ideal mesocyclone centered on this two-dimensional array could form the mean vector  $\vec{m}$ . The distances

between this mean vector and corresponding data vectors must be compared with a suitable threshold and when they are smaller than this threshold, a detection of the mesocyclone is declared.

The Mahalanobis distance (Tou and Gonzales, 1974)

$$d_m = (\vec{x}-\vec{m})^T C^{-1} (\vec{x}-\vec{m}) \quad (2)$$

is actually the negative of the logarithm of the likelihood function (if  $\vec{x}-\vec{m}$  has a Gaussian distribution).  $C^{-1}$  is the inverse of the covariance matrix of the pattern population and T signifies a transpose of a vector.

Distance measure  $d_m$  requires a large number of calculations and furthermore determination of mean pattern vector  $\vec{m}$  and the covariance matrix C is complicated. The complication arises because the mesocyclone signature of a vortex with a constant diameter is a function of range and at a same range mesocyclones of different size would require mean vectors with different number of elements. Therefore, an adaptive mean vector would have to be constructed.

Correlation techniques have pretty much the same type of problems as distance measuring techniques. They require maximization of a correlation coefficient between the mean vector and the data vector.

Substantial storage of data is required when distance or correlation techniques are used. If the pattern vector for the model consists of data from M radial, then at any one time at least M radials of data must be stored in memory so that they can fast be made available for calculations.

The pattern recognition method employed in this study relies on recognition of attributes that mesocyclones possess. Significant attributes have been obtained from previous measurements (Burgess et al., 1979). Our algorithm requires simultaneous storage of only two radials of velocities and should, therefore, be suitable for real-time applications.

Table 1

Technique	Number of Operations	Number of Storage Locations
Distance $d_e$	$2M^2 \cdot (N-M+1)^2$	M · N
Distance $d_m$	$2(2M^2+M^4)(N-M+1)^2$	M · N
Correlation	$2M^2(N-M+1)^2$	M · N
Pattern Recognition	$M^2(N-M+1)^2$	2N

The number of computations and storage requirements for the four pattern recognition techniques are compared in Table 1. It is assumed that the

mesocyclone signature (i.e., pattern vector  $\vec{m}$ ) consists of  $M \times M$  model velocity points (at  $M$  discrete azimuths and  $M$  range locations). Let the sector of data that encompass the storm consist of an  $N \times N$  array (range, azimuth) of velocities. The number of operations for the first three algorithms is the total number of additions and multiplications. For example, one  $d_e$  calculation requires  $M^2$  multiplications (one for each data point to generate normalized velocities) and  $M^2$  subtractions (when the model vector is subtracted from a chosen subset of data values). Since there are  $(N-M+1)^2$  distances to be calculated, the total number of additions and multiplications is  $2 M^2 (N-M+1)^2$ . It is shown in the next section that for our algorithm the operations are comparisons of velocities between two adjacent radials and at the same range locations. The advantages of this algorithm are: 1) It adapts itself automatically to the size of the mesocyclone; that is, there is no need to assume a representative size as ground truth; 2) operations are comparisons which are much faster than multiplications or additions; 3) it requires storage of only two consecutive radials of data in addition to the candidate vectors that may be part of the mesocyclone or shear lines; and 4) it does not require normalization by size or velocity.

#### 4. THE ALGORITHM

The first step in the algorithm (flow chart in Figure 2) is a search for Doppler velocity gradients. This is accomplished by identifying either a consistent increase or decrease of velocities in the azimuthal direction. The algorithm is designed to recognize only cyclonic rotation and was meant to do so on the velocities within the mesocyclone core. Therefore, with clockwise antenna rotation increasing velocities are sought and with counterclockwise rotation the decreasing ones. When a run of (at least two data points are required to form a run) increasing or decreasing velocities terminates, a pattern vector is formed. The five components of the pattern vector are the beginning azimuth  $\phi_b$ , the ending azimuth  $\phi_e$ , the beginning velocity  $v_b$ , the ending velocity  $v_e$ , and the range  $r$ . Each pattern vector must pass three tests before it is saved for future analysis.

The first test the vector must pass is a low "Doppler angular momentum" threshold. The pattern vector must originate from data that have sufficient "angular momentum" to be considered for further analysis. The momentum is estimated from the product of the measured Doppler velocity difference ( $v_e - v_b$ )

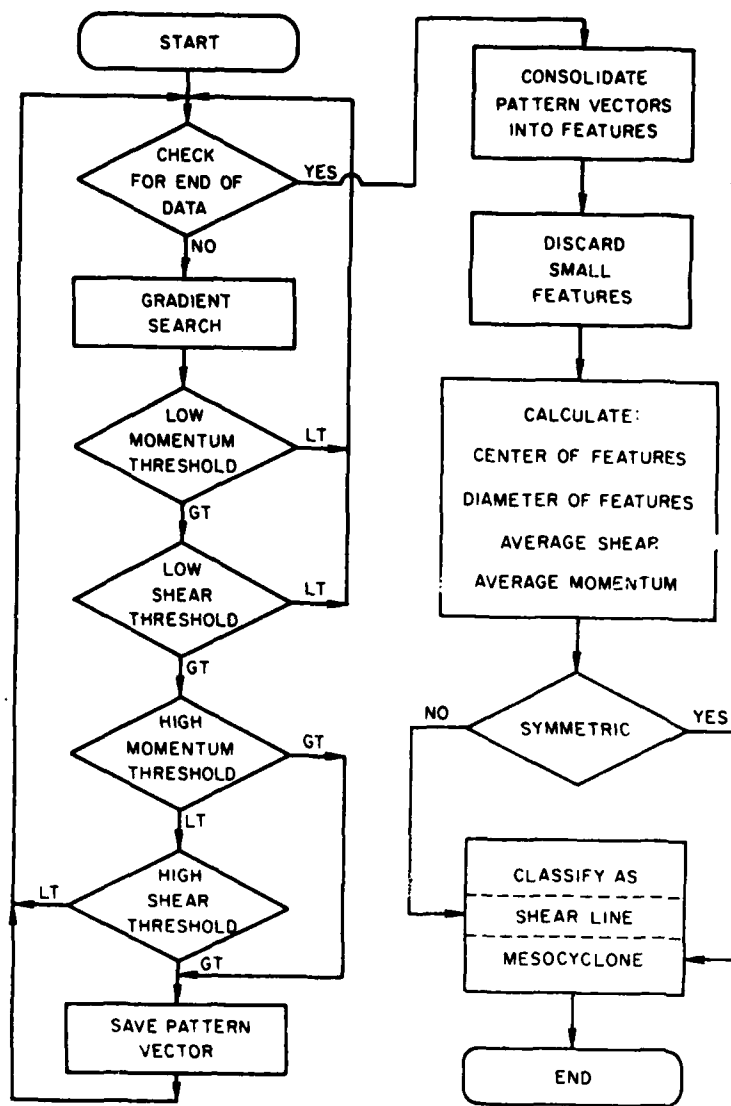


Figure 2. Block diagram of pattern recognition algorithm.

and the azimuthal distance  $r(\phi_e - \phi_b)$  stored in the pattern vector. Therefore, the calculated momentum often may not correspond to a rotating air mass, but rather to a shear region. Nevertheless, this first step is designed to filter out a large percentage of the radar data so that the more extensive analysis is performed only on the remaining pertinent data. A mesocyclone at its earliest stages may have a large diameter, and while the shear may not be significant, the angular momentum may be higher than it will be throughout the rest of its lifetime (i.e., the angular momentum as measured by the radar in a horizontal plane may decrease towards tornado time). The second test uses a low shear threshold to remove anything below the background shear value of  $2 \cdot 10^{-3} \text{ s}^{-1}$  (see Burgess, 1976). In the third test, the pattern vector is reported if it passes either a high momentum threshold or a high shear threshold. Since shear is the more dominant feature during the mature stage, it is used even if the pattern vector does not pass the high momentum threshold. Two thresholds are needed to accommodate variations in the mesocyclone from its early stages to the more mature stage.

Figure 3 shows the detection region in the momentum-shear plane.  $L_s$  and  $L_m$  are low shear and momentum thresholds whereas  $H_s$  and  $H_m$  are the high thresholds. Tests on data are needed to establish optimum values of these thresholds, and if they should vary with range from radar. In the present study the following values have been utilized:

$$\begin{array}{ll} L_s = 2 \text{ m} \cdot \text{s}^{-1} / \text{km} & H_s = 4 \text{ m} \cdot \text{s}^{-1} / \text{km} \\ L_m = 50 \text{ m} \cdot \text{s}^{-1} \cdot \text{km} & H_m = 150 \text{ m} \cdot \text{s}^{-1} \cdot \text{km} \end{array}$$

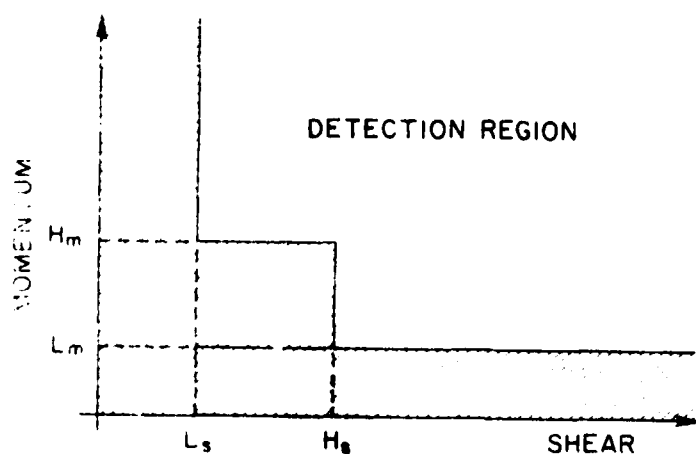


Figure 3. Decision boundary in the shear-momentum space. The thresholds are indicated.

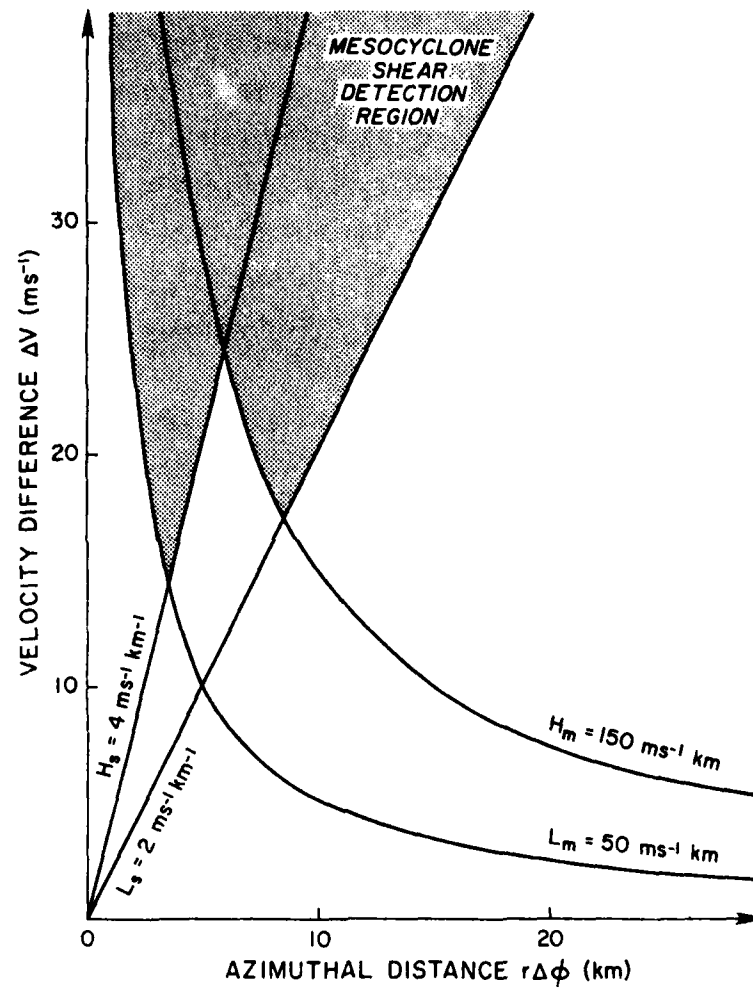


Figure 4. Decision boundary in the velocity difference - azimuthal distance space with actual thresholds used by the algorithm.

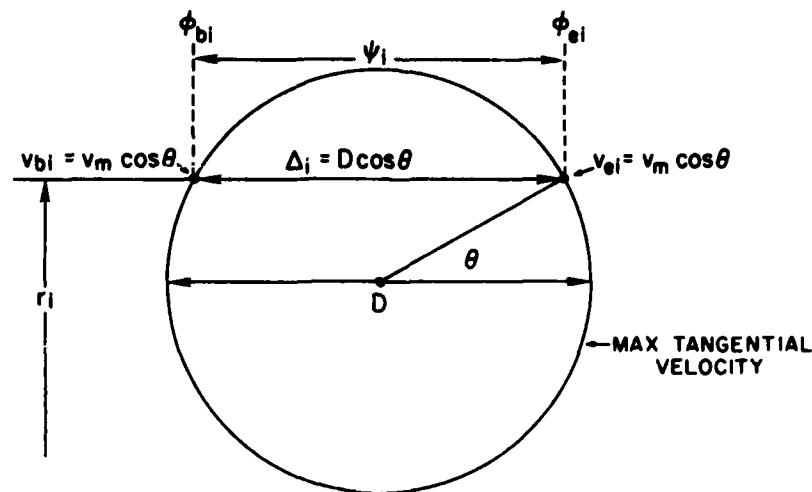


An alternate view of the detection region (Figure 4) is obtained if the velocity difference is plotted versus the azimuthal distance. In both Figure 3 and 4 the somewhat peculiar region ( $L_s < \text{shear} < H_s$  and  $L_m < \text{momentum} < H_m$ ) of no detection is clearly visible. This whole region or a part of it could be included into the detection area in which case we would expect an increase in both the probability of false alarm and detection.

After a field of data has been filtered by the aforementioned tests, the pattern vectors are consolidated according to their relative spatial proximities. Azimuthal and range distances between one (comparing) vector and all other already sorted vectors are computed. Whenever the comparing vector is found with a center closer than  $2.2^\circ$  in azimuth and 1 km in range to a sorted vector, it is put in the same feature as the sorted vector. These values are not based on firm theoretical or experimental grounds. The one kilometer separation in range will insure that at least two pattern vectors are contained within a rotation that has a diameter of 2 km which is considered to be about the minimum for mesocyclones. A larger spacing in azimuth (for ranges over 30 km from the radar) allows to group vectors that are azimuthally overlapping but have centers that are further apart. Optimum value of the azimuthal separation may be a function of range and together with the range separation needs to be further investigated. When the comparisons of the current comparing vector with sorted vectors is exhausted, one of the not yet sorted vectors becomes a comparing vector and the process is repeated. The output of the sorting routine is a set of features, each consisting of several pattern vectors. A feature with only a few pattern vectors is discarded. The minimum number of pattern vectors in a candidate feature must be such to encompass a mesocyclone with minimum core diameter (about 2 km). The average and maximum shears, average and maximum rotational speeds, average momentum, and two lengths (diameters) are calculated for each feature. One length is for the radial size, and the other for the azimuthal size. If the two lengths disagree by more than a factor of two (i.e., the feature is not symmetrical), the feature is discarded. However, when the radial length is large compared to the azimuthal one or vice versa, the feature can be classified as a shear region.

Two slightly different methods are suggested to calculate the average azimuthal "diameter". In one the "diameter"  $D_1$  is weighted by the "momentum", and is calculated from:

$$D_1 = \sum \Delta_i^2 v_i / \sum \Delta_i v_i \quad (3)$$



where the azimuthal distance  $\Delta_i = r_i \psi_i$  at an  $i^{\text{th}}$  range gate,  $v_i = v_{ei} - v_{bi}$ , and  $\psi_i = \phi_{bi} - \phi_{ei}$ .

$$v_{bi} = -v_m \cos \theta; v_{ei} = v_m \cos \theta \quad (4)$$

$$D_1 = D \int_0^{\pi/2} \cos^3 \theta / \int_0^{\pi/2} \cos^2 \theta = 8D/3\pi \quad (5)$$

The second method calculates the "diameter" from:

which similarly to (5) produces a theoretical relationship:

$$D_2 = D \int_0^{\pi/2} \cos^2 \theta d\theta / \int_0^{\pi/2} \cos \theta b \theta = D\pi/4 \quad (7)$$

Factors multiplying D in (5) and (7) are close, and it remains to be determined which weighting defines better a mesocyclone diameter.

A correction factor would also be needed if a simple average of azimuthal distances is used for estimating the diameter. The relationships then are:

$$D_3 = \sum \Delta_i = 2 \int_0^{\pi/2} D \cos \theta = 2D \quad (8)$$

Our experience with mesocyclones is that the Doppler velocity couplet defining the maximum speeds of mesocyclones (smallest closed contours on Figure 1) conforms well with theoretical predictions but other velocity contours may deviate considerably from the model. Weighting by the momentum restores some symmetry and gives significance to the data that inherently correspond better to the model. Furthermore data across the maximum  $\Delta_i$  would be less contaminated by errors. For these same reasons, azimuthal center  $\phi_c$  and range center  $r_c$  of the mesocyclone are obtained by weighting the ranges  $r_i$  and azimuthal centers  $\phi_{ci} = (\phi_{bi} + \phi_{ei})/2$  of vectors with  $\psi_i v_i$

$$r_c = \sum r_i \psi_i v_i / \sum \psi_i v_i \quad (9)$$

$$\phi_c = \sum \phi_{ci} \psi_i v_i / \sum \psi_i v_i \quad (10)$$

Calculations of  $D_1$  and  $D_2$  in the program are slightly at variance with (3) and (6). In order to preserve computational speed,  $r_i$  which is almost constant is pulled out of the summation and replaced with (9), thus:

$$D_1 = r_c \sum \phi_i^2 v_i / \sum \phi_i v_i \quad (11)$$

$$D_2 = r_c \sum \phi_i^2 / \sum \phi_i \quad (12)$$

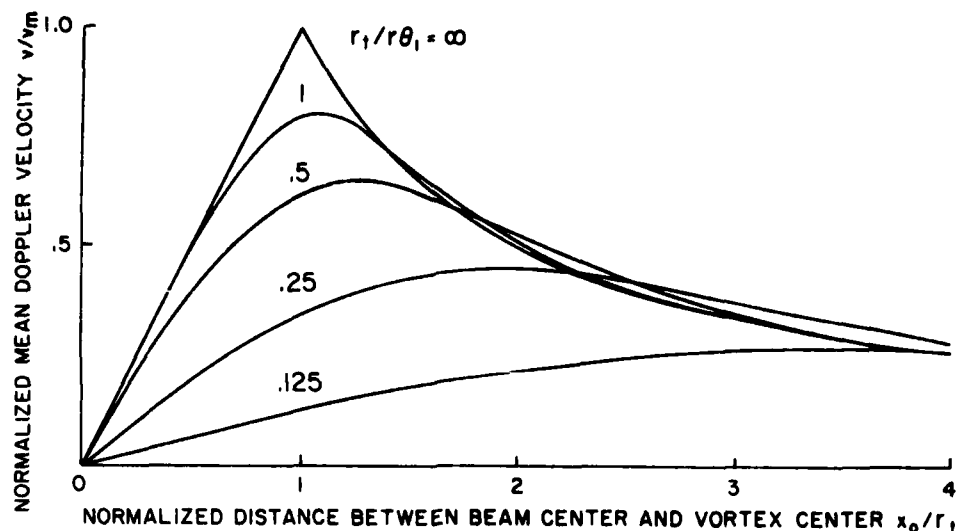


Figure 6. Normalized Doppler velocities of a combined Rankine model vortex centered at a radar range  $r$ . Vortex radius is  $r_t$  and the range resolution is much finer than the size of the mesocyclone.

Presently, the program classifies as mesocyclones all features for which the ratio of the radial to azimuthal diameters lies within 0.5 to 2. We need to gain more experience in order to firm up this criterion. However, consideration of resolution at the furthest range of interest (250 km) points out that, with a  $1^\circ$  antenna beamwidth, a mesocyclone having a solid core diameter of 2 km (out of 37 mesocyclones observed between 1971 and 1975, only in one case was the diameter as small as 2 km (Burgess, 1976)) would seem to have an azimuthal diameter twice as large (i.e., 4 km).

This can be demonstrated observing Figure 6 which is a plot of normalized mean Doppler velocity versus normalized distance between beam center and vortex center for a radar range that is centered on the vortex. The vortex is a Rankine combined model and range resolution is assumed to be perfect.

## 5. PRELIMINARY RESULTS

To date, we have preliminary results from two cases. The first storm produced the mesocyclone on April 30, 1978, and spawned a maxi-tornado which

destroyed 25 homes in and near Piedmont, Oklahoma (Burgess et al. 1979). Five different times have been examined.

Comparisons between mesocyclone parameters obtained by the algorithm and subjectively deduced values from mean Doppler velocities are shown in Figure 7 and Figure 8. The agreement, in general, is quite good; for all five locations the two positions are within the radius of the mesocyclone and the tracks are almost identical. Note that the subjectively determined diameters are somewhat smaller. This is not surprising because the two methods for estimating the diameter differ. The meteorologist who estimated the diameters, used the distance between peak velocities (i.e., the farthest closed isodops as in Figure 1). On the other hand, the algorithm calculates the weighted average of distances between the peak velocities in a feature (Eq. 11). No attempt has yet been made to account for smoothing by the radar resolution volume.

The average shear calculated by the algorithm from the pattern vectors of the mesocyclone feature follows the same trend as the maximum shear determined subjectively (Figure 8). A somewhat large difference occurs at the latest time when the maxi-tornado formed and the subjectively measured shear was influenced by the tornado vortex signature. Since the maximum shear is contained in one of the pattern vectors, with a simple modification of the program, it could be easily retrieved.

The second storm on which the algorithm was tested occurred on May 22, 1981, west of Norman and produced several very large tornadoes. One example of a mesocyclone feature in a range versus azimuth display of velocities is shown on Figure 9. The total of 32 vectors are in this feature. Two vectors, bracketed by dashed lines towards the top, were not detected because of weak momentum. However, the vector above them was detected and placed in the feature due to its proximity to the vector at 68.68 km. The star on this figure locates the mesocyclone center computed from Eqs. (9), (10).

Figure 10 illustrates what appears to be two separate features detected by the algorithm. Upon closer examination of the velocity field, we note that there were several non-valid velocities (999) between the two features. The algorithm would have detected four vectors (at 65.8, 65.9, 66.1, 66.2 km) if the non-valid velocities at 282.7° and 281.2° were bypassed. Then the gap between the closest vectors in range would have been less than 1 km and all would be classified as a single feature. The following modification could accommodate such situations: If there is an isolated (in azimuth) non-valid data (i.e., velocity at a very weak

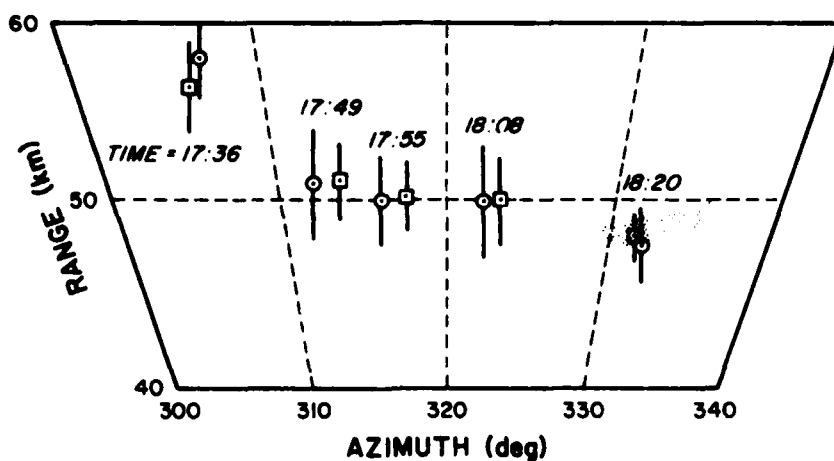


Figure 7. Azimuth versus range display of mesocyclone position and diameter. Bars with circles depict the diameter  $D_1$  and position produced by the algorithm, whereas bars with squares are values subjectively calculated from Doppler velocity fields. Maxi-tornado damage path is stippled area.

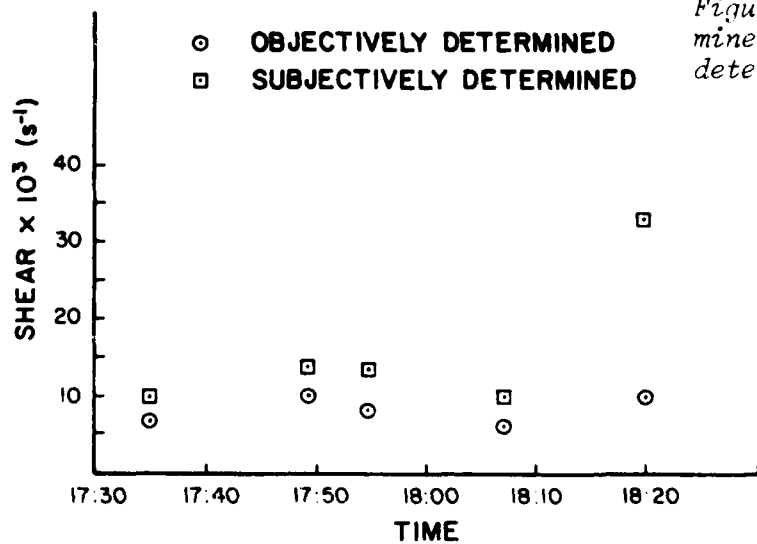


Figure 8. Plot of objectively determined average shear and subjectively determined maximum shear.

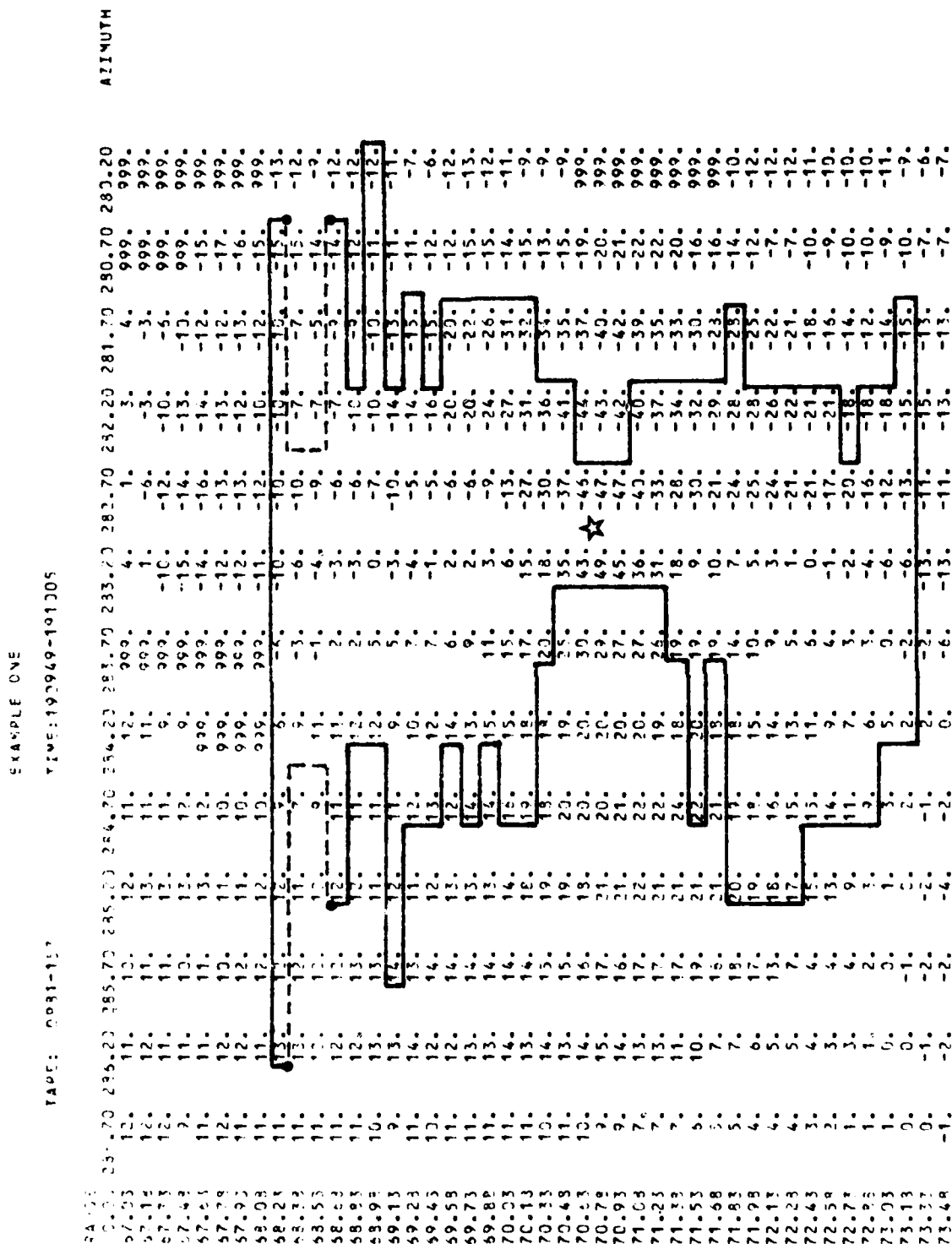
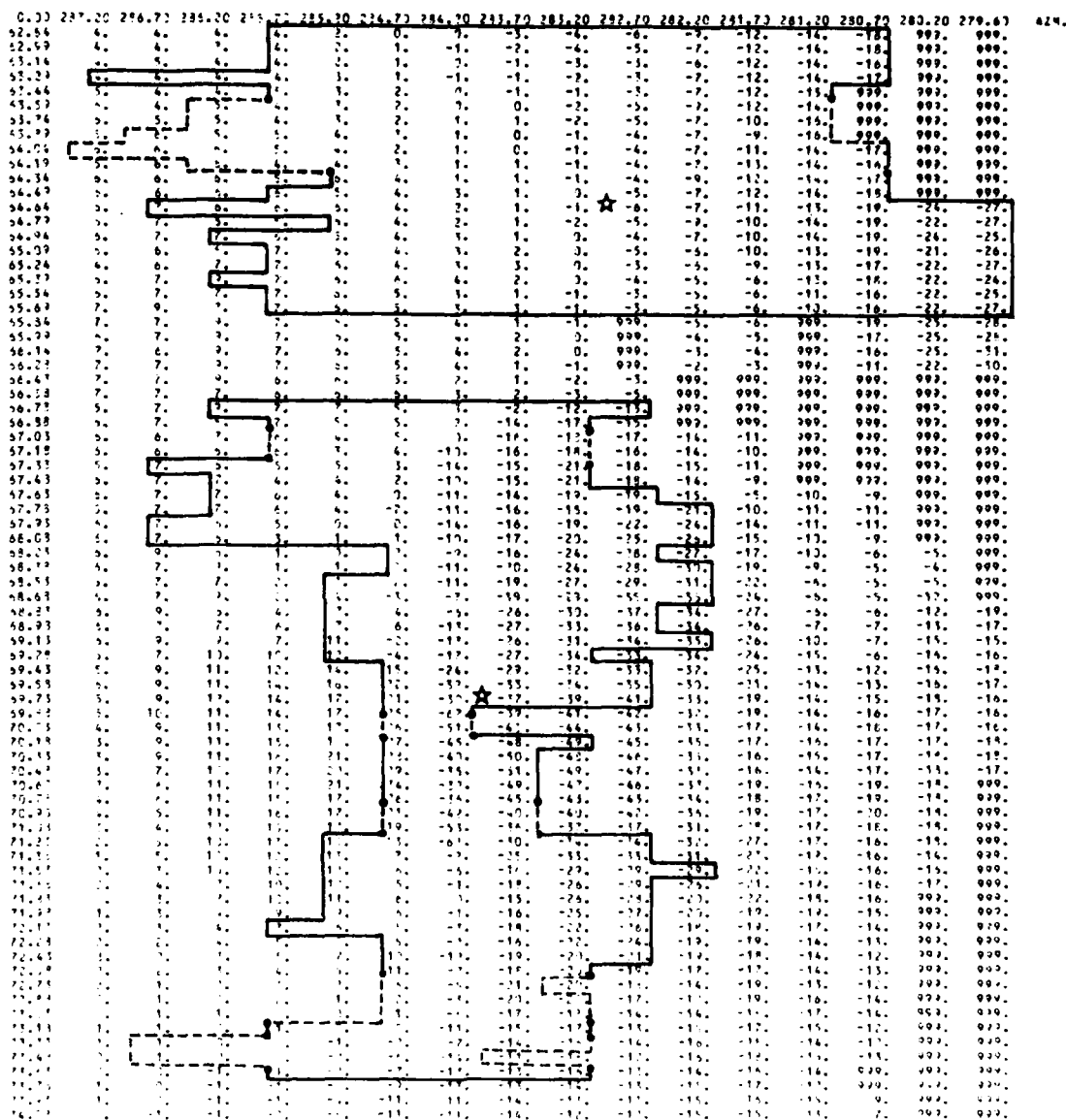


Figure 8. Mesocyclone feature detected by the algorithm. Velocities are printed in an azimuth (on abscissa) versus range (ordinate) format. Elevation angle is 1.0°. Solid lines bracket all detected vectors of a feature. Dashed lines correspond to two nondetected vectors.

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reflectivity or a radial of bad values), assign to it the value of the adjacent (previous azimuth) velocity and proceed with normal vector calculations. If there are 2 bad adjacent velocities, stop the run and start the new vector. In this way, still only two radials at a time are needed and one additional array of flag values, and yet isolated bad data would not cause disruption of the vector calculations. Of course, at the expense of more storage and computing time one could treat two consecutive bad data as well as situations where there is a slight reversal in gradient (i.e., one or two data points). It is noteworthy that the vector at 70.03 km ( $v_b = -51 \text{ m}\cdot\text{s}^{-1}$ ,  $v_e = 26 \text{ m}\cdot\text{s}^{-1}$ ) was not detected. Even though the shear is very large, the momentum is weak and thus the data do not pass our test. Because such situations may occur with tornadoes, it may prove useful to include an extremely high shear threshold in combination with our test.

Three consecutive scans (in elevation) with the size and location of a mesocyclone detected by the algorithm are shown on Figure 11a, b, and c. Note again a split detection of the mesocyclone at times 1 and 2 (Figure 11a). The case at time 1 corresponds to Figure 10, but the split at time 2 occurred for a different reason: Namely, the momentum and shear between the two features were very weak.

On the scan above (Figure 11b) we note another split signature at time 2. The reason for the split now is that the vector centers are separated in azimuth (although close in range). It appears that intense circulation is developing at 65 km west and 9 km north ( $\Delta$ ) where the maximum shear was  $55 \text{ m}\cdot\text{s}^{-1}/\text{km}$  and maximum momentum is  $405 \text{ m}\cdot\text{s}^{-1}\cdot\text{km}$ . The feature whose center is marked with o had the following maximum shear and momentums: at time 1, max shear =  $9 \text{ m}\cdot\text{s}^{-1}/\text{km}$ ; max momentum =  $405 \text{ m}\cdot\text{s}^{-1}\cdot\text{km}$ . Clearly the  $\Delta$  feature is part of the larger circulation and was contained in its feature at time 1 as evidenced by the large shear. With the split the feature  $\Delta$  took with it the large shear. The split here could have been prevented if somewhat larger distances between vectors were allowed in the sorting routine. This criterion is again a subject of current investigations.

The Figure 11c at  $5.4^\circ$  elevation shows two consecutive positions of the mesocyclone (time 1 and 2) which were quite well detected.

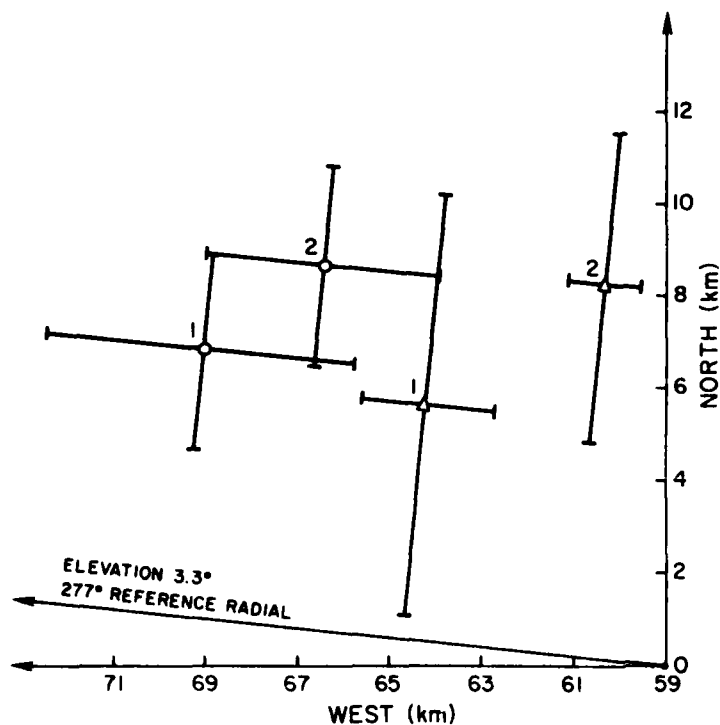


Figure 11a. The position and sizes of features detected at two consecutive scans and same elevation  $3.3^\circ$ . (1 and 2) separated by 6 minutes. Azimuthal diameters are indicated with vertical lines and range diameters with horizontal lines. Two features  $\Delta$  and  $\circ$  were detected in both scans. The two features in the first scan (1) correspond to the ones on Figure 9.

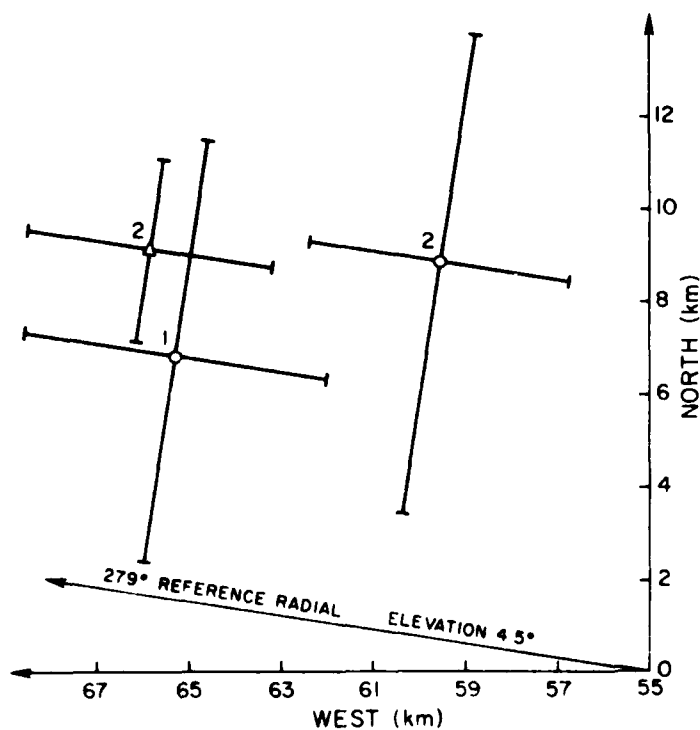
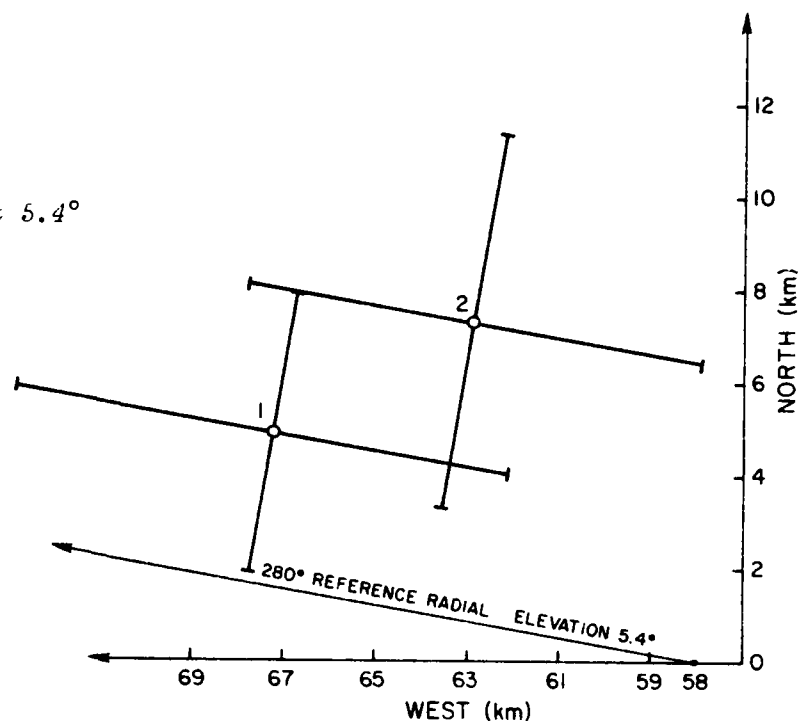


Figure 11b. Same as 11a but at the next elevation angle ( $4.5^\circ$ ).

Figure 11c. Same as 11a but at  $5.4^\circ$  in elevation.



## 6. CONCLUSION

A novel pattern recognition algorithm for detecting mesocyclonic shear from single Doppler radar data has been developed. The method is based on extracting features that characterize mesocyclones. It operates simultaneously on two radials of velocities, utilizes relatively simple computational techniques, and should, therefore, be applicable to real-time operational systems. Preliminary results on a limited data set are encouraging; however, further comprehensive testing is needed to establish optimum thresholds and their range dependence.

During the course of this study, some simple modifications of the algorithm that could increase its accuracy and usefulness became apparent. 1) For instance, the maximum measured shear and momentum could be printed out. 2) In order to avoid loss of vectors with very high shear but small momentum such as in the center of the tornado vortex signature, it may be advisable to include in an OR combination with our test a very high shear test. 3) Presently, an isolated bad velocity (in azimuth) signals the end of a vector; this need not be so, to preserve storage and speed two consecutive invalid points could signal the end of a

vector. 4) The optimum values of azimuthal and range distance that vectors must satisfy to form a feature should be established. 5) Optimum momentum and shear thresholds need to be determined.

The present version of the algorithm does not consider the time and height continuity of the circulation but such an addition is quite straightforward. There may be other modifications that we cannot foresee without extensive tests on various data sets. This would also help us establish the false alarm rates and detection probabilities per scan.

## 7. ACKNOWLEDGMENTS

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## APPENDIX A

### Program Description

The mesocyclone detection program requires radials of preprocessed velocity data. Preprocessing involves assignment of correct ranges to velocity estimates, thresholding and properly scaling these estimates, and reading and sorting out various housekeeping information. Preprocessing the mesocyclone program and the various subroutines of the mesocyclone program are described in this appendix.

#### A1. Preprocessing

Preprocessing starts with the routine RDREC that is called for every radial (see Figure A.1).

##### For Every Radial:

1. Read raw data and strip and identify housekeeping--subroutine RWDP81

Sample call: CALL RWDP81(W, ISKP, LTIM, LINT)

W--logical unit number assigned to tape drive

ISKP-1: skip 1 record

2: decode housekeeping only

3: decode housekeeping, intensities and time data

4: decode intensities and time series without reading a record

800: change mode

0: reset all gate alignments to 1

9: rewind tape

LTIM-1: decode time series data

0: don't decode time series

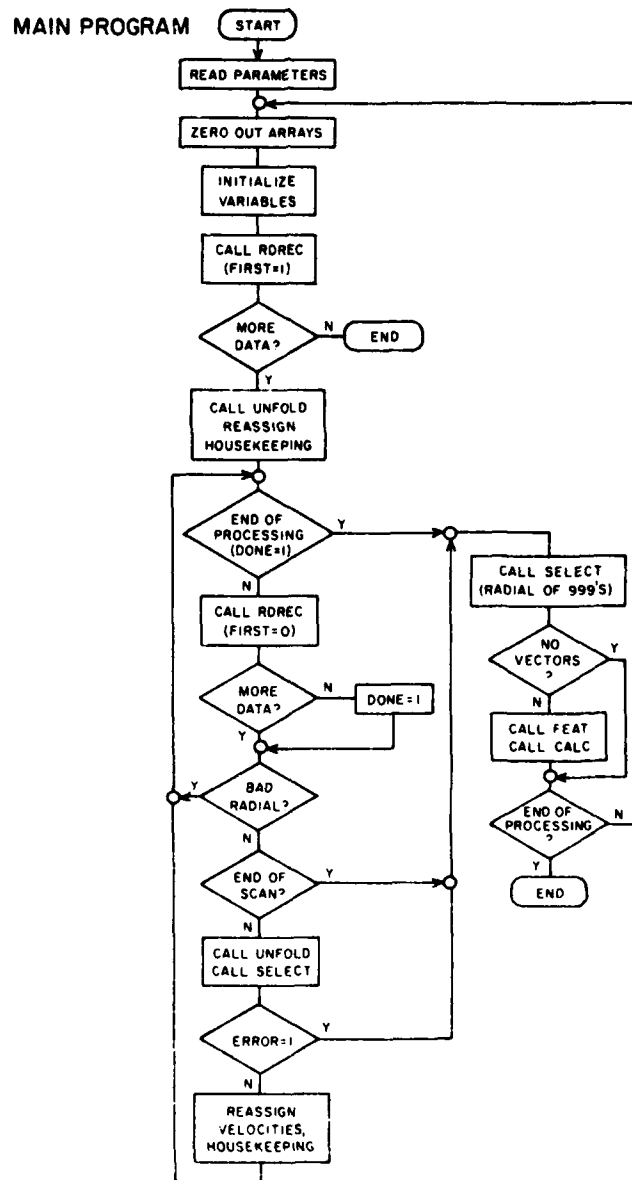


Figure A.1 Flow chart of the Main Program.

LINT-1: decode integrator PPP data

0: don't decode PPP data

The typical call from the mesocyclone program is: CALL RWDP81(10,3,0,1)

2. Assign correct ranges to velocity estimates. This is needed when interlaced transmission for estimating separately velocities and reflectivities is used.

Subroutine DEXPAND

Sample call: CALL DEXPAND(IVCINT,RVCPMP,RSDPMP,STN,IB,IE,IDEL,  
SNRT,VT,STDT,INT,VEL,STD)

IVCINT-integrator array from RWDP81

RVCPMP-velocity array from RWDP81

RSDPMP-spectrum width array from RWDP81

STN-signal-to-noise ratio array - 64 values

IB-beginning range gate for processing

IE-ending range gate for processing

IDEL-required gate spacing

SNRT-signal-to-noise ratio threshold

VT-velocity threshold

STDT-spectrum width threshold

INT-expanded integrator array

VEL-dealiased velocity array

STD-unbiased spectrum width array (not used by the program)

Typical call from mesocyclone program: CALL DEXPAND(IVCINT, RVCPMP,  
RSDPMP, STN,1,1524,1,0,10,15,OUT, OUT1, OUT2)

where OUT is an integer array dimensioned 1524 and OUT1 and OUT2 are real arrays dimensioned 1524

At NSSL the interlaced transmission uses a pulse separation time for reflectivity estimation that is four times the one for velocity estimation. However, in our program only the first two ambiguous trips for velocity estimation are considered. Since the number of usable range gates for velocity estimation is 762, for two trips the total number of locations is twice 762 or 1524.

3. Calculate reflectivities: subroutine CALREF

Sample call: CALL CALREF(OUT,REFL,STN,RANGE, LOGR,CNST)

OUT: integrator array passed from DPEXPAND

REFL: array of reflectivities at each range gate processed in  
DPEXPAND (dimensioned same as OUT)

STN: signal-to-noise ratio array (64 values)

RANGE: array (dimensioned same as OUT) containing the range in kilometers  
to each range gate

LOGR: array (dimensioned same as RANGE) containing  $\text{LOGR}(I) = 2\text{Log}_{10}$   
( $\text{RANGE}(I)$ ) where I represents the range gate number

CNST: a constant needed for calculation of reflectivities  
 $\text{CNST} = \text{CN} * 10 - 110.8$  where CN is the result of a call to the  
function RADARCON

RANGE, LOGR, and CNST are calculated in subroutine PRELIM of the  
mesocyclone program.

The call of subroutine CALREF in the program looks exactly like the  
sample call above.

For Each Scan:

1. calculate range to the first range gate and distance between range  
gates in kilometers - subroutine DOPRNG81



Sample call: CALL DOPRNG81(DATE,BRG,DRG,V)

DATE: day data were collected (i.e., 052281)

BRG: range to first range gate in km

DRG: range between gates in km

V: Nyquist velocity (not used in program)

2. Calculate a constant (CN) which determines the constant (CNST), used to calculate reflectivities - function RADARCON

Sample call: CN=RADARCON(BH,BW,P,WL,G,POW)

BH: vertical beamwidth in degrees

BW: horizontal beamwidth in degrees

P: pulse width in microseconds

WL: wavelength of transmitted electromagnetic field in centimeters

G: antenna gain in DB

POW: peak transmitter power in kilowatts

Typical call from mesocyclone program: CN=RADARCON(0.8,0.8,1.0,10.52,  
46.8,750.0)

## A2. Mesocyclone Program

### Input to Mesocyclone Program

A. From preprocessing - passed through common blocks and subroutine calls

#### 1. one radial of data

OUT1 - array returned from subroutine DPEXPAND contains real velocities, which are changed to integers and assigned to array VEL by subroutine RDREC in meso program.

REFL - array returned from subroutine CALREF - contains reflectivities. These are checked against a lowest needed reflectivity value (RTH), and velocities corresponding to reflectivities below this level are not processed.

#### 2. Housekeeping Data

NTIME - time current radial was collected

AZM - azimuth angle of current radial

ELEV - antenna elevation angle during current scan

STATUS - tape status indicator (after last read)

0: end-of-file

1: bad record was read

-1: good record was read

ITYPE - record type

0: Bad    1: Time series    2: Pulse pair

ISTAT - Station code

1: Norman    2: Cimarron

IPRTSW - pulse repetition time indicator

RPRT - constant proportional to the pulse repetition time.

The relationship between the switch and RPRT and the true pulse repetition time is as follows:

IPRTSW	RPRT	True pulse repetition time	
		RPRT*0.768 ms	
0	1.0	0.768	ms
1	1.2	0.921	ms
2	1.4	1.075	ms
3	1.6	1.228	ms

IDELAZ - azimuth step value indicator

1: 0.50 2: 1.0° 3: 2.0°

IAZMD - azimuthal antenna direction indicator

1: counterclockwise 3: clockwise

#### B. OTHER INPUT DATA

##### 1. read from files

SHEART, HSHEAR, THRESH, LOWTH - thresholds used in detecting velocity runs. See explanation of subroutine SELECT

M, N, R - values used to sort features - see description of subroutine FEAT

RTH - reflectivity threshold - it has been found experimentally that mesocyclones do not occur in regions with reflectivities below this threshold. Therefore, to save computer time, velocities corresponding to reflectivities below this level are ignored.

ELTH - elevation limit - This limit is set to correspond to a height of about 8 km at the storm location. Above this height the circulation signature changes into a divergence pattern and can not be detected with the mesocyclone algorithm.

## OUTPUT DATA

One line of output is printed at the beginning of each scan. Also each feature's vectors are printed out along with feature attributes after each scan.

A. Printouts at the beginning of scan are:

1. Direction of the antenna in coded form  
(see IAZMD under housekeeping input)
2. Elevation angle of the radar antenna (see ELEV under housekeeping input)
3. The time of the collection of the first radial of the scan  
(see NTIME under housekeeping input)

### OUTPUT FOR EACH FEATURE:

B. Features - array LIST(I,J,K) where I = feature number, J = vector number and K = attribute of vector number.

A feature is a group of vectors, each vector representing a velocity run at a constant range. Each vector has the following seven attributes:

1. range to the run in kilometers
2. azimuth angle where the run began
3. azimuth angle where the run finished
4. velocity recorded where the run began
5. velocity recorded where the run ended
6. the calculated momentum of the run.
7. the calculated shear of the run.

- C. Feature attributes - array AFEAT(I,J) where I = feature number,  
J = attribute (of feature) number
1. number of vectors in the feature
  2. lowest azimuth angle in the feature in degrees
  3. highest azimuth angle in the feature in degrees
  4. lowest range in feature in kilometers
  5. highest range in feature in kilometers
- D. Other feature attributes (not in the array AFEAT)
1. momentum weighted center of the feature (azimuth and range, array PT)
  2. azimuthal diameter of feature - weighted by momentum (DIAMAZ)
  3. unweighted azimuthal diameter (ODIAM)
  4. unweighted radial diameter (DIAMR)
  5. ratio DIAMAZ/DIAMR for symmetry considerations
  6. Average shear of feature (AVGSHR)
  7. Maximum shear of feature (MAXSH)
  8. Average momentum of the feature (AVGMOM)
  9. Average rotational speed of feature (AVGSP)
  10. Maximum rotational speed of feature (MAXSP)

### A.3. Description of Routines

#### MAIN PROGRAM

The main program's function is to control the processing done by the subroutines. Its flow chart is on Figure A.1 and the control proceeds in the following order:

#### Preliminary

1. read variables from files
2. initialize STATUS, NTIME, DONE
3. enter beginning and ending processing times on terminal  
(IBEG, IENDT)

#### For Every Scan

4. zero out vector and feature lists (VECTOR, LIST)
5. initialize ERROR(=0), COUNT(=0), and FIRST(=1)
6. read one needed radial (CALL RDREC)
7. check STATUS 0: end program else continue
8. write important information
9. zero out CODE array and reassign VEL to OLDVEL
10. dealias OLDVEL and reassign housekeeping
11. check DONE 1: end program else continue
12. read one needed radial (CALL RDREC) (FIRST=0)
13. check STATUS 0: DONE=1
14. bad radial yes: Go to 11 No: continue
15. end of scan? yes: reassign aximuthal direction (IAD) and go to 19  
no: continue
16. dealias VEL, search for runs (CALL SELECT)
17. OLDVEL=VEL, reassign housekeeping

18. go to 11
19. VEL=999's (means not usable velocities), reassign IAD
20. search for runs
21. no vectors? Yes: go to 23 No: continue
22. Assemble features (CALL FEAT) and calculate feature attributes  
(CALL CALC)
23. check DONE 0: go to 4 1: end program

#### SUBROUTINE SELECT

The flow chart of this subroutine is shown on Figure A.2. It operates on two consecutive radials of velocity data, OLDVEL and VEL. The purpose of the routine is to search at every range gate for changing velocities with respect to azimuth angle. The array CODE keeps track of velocity trends (at every range gate) as of the last call to SELECT

#### Values of CODE elements and their meanings

<u>Value</u>	<u>Tendency</u>
0	constant velocities (no run is going on)
-1	decreasing velocities (run is on)
1	increasing velocity (run is on)

The routine executes a DO loop with an index from 1 to 1524 called I. On each execution of the statements in the loop, OLDVEL(I) is compared to VEL(I). This tendency is compared to CODE(I). 999's cause a termination of an ongoing run.

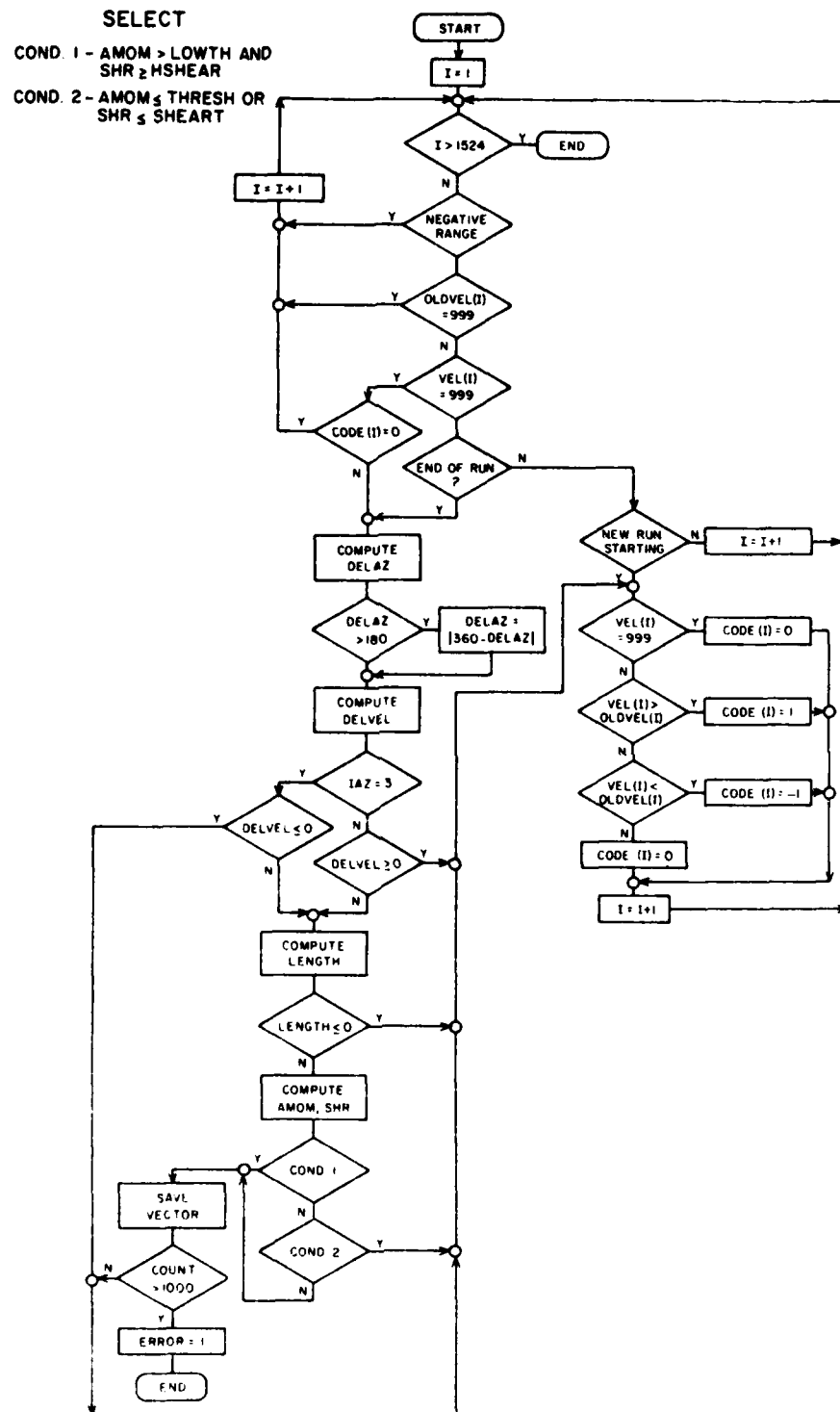


Figure A.2 Flow chart of the Subroutine SELECT.



<u>CODE(I)</u>	<u>OLDVEL(I)=VEL(I)</u>	<u>OLDVEL(I)&lt;VEL(I)</u>	<u>OLDVEL(I)&gt;VEL(I)</u>
0	constant velocity	start increasing run	start decreasing run
1	continue increasing run	continue increasing run	finish increasing run and start decreasing run
-1	continue decreasing run	finish decreasing run and start increasing run	continue decreasing run

Control proceeds as follows:

1. I=1
2. a) constant velocities or continuing run: go to 3  
b) starting a run: go to START NEW RUN  
c) ending a run: go to END RUN
3. I=I+1
4. I>1524: return to main program else: go to 2

END RUN:

- a)  $ENDVEL = (OLDVEL(I) * 1.07) / RPRT$  last velocity of run  
 $ENDAZ = OLDZ$  last azimuth of run  
 $DELVEL = ENDVEL - BEGBEL(I)$  velocity change of run  
 $DELAZ = |ENDAZ - BEGAZ(I)|$  azimuth change of run
- b) Throw out unwanted runs (only runs consistent with cyclonic circulation are kept.)  
clockwise antenna rotation: throw out if  $DELVEL \leq 0$   
counterclockwise rotation: throw out if  $DELVEL > 0$   
if run is thrown out: go to START NEW RUN  
else: continue

c)  $LENGTH = DELAZ \text{ CON } RANGE(I) \quad CON = \pi/180$

$DELVEL = |DELVEL|$

if  $LENGTH \leq 0$ : go to START NEW RUN; else: continue

d)  $AMDM = DELVEL(LENGTH)$  momentum of run

$SHR = DELVEL/LENGTH$  shear of run

e) if  $AMOM \geq LDWTH$  and  $SHR \geq HSHEAR$  then go to f)

if  $AMOM \leq THRESH$  or  $SHR \leq SHEART$  then go to START NEW RUN

else: continue

f) save vector ( $COUNT = COUNT + 1$ )

too many vectors: return to main program

else: go to START NEW RUN

START NEW RUN:

a)  $VEL(I) = 999$ :  $CODE(I) = 0$ , go to e)

else: continue

b) increasing velocities:  $CODE(I) = 1$ , go to e)

else: continue

c) decreasing velocities:  $CODE(I) = -1$ , go to e)

else: continue

d)  $CODE(I) = 0$

e)  $BEGVEL(I) = OLDVEL(I)(1.07)/PRT$

$BEGAZ(I) = OLDAZ$

go to 3.

THRESHOLDS:

Shear and momentum thresholds and their presently used values are:

low shear:  $SHEART = 2.0 \text{ (m} \cdot \text{s}^{-1} / \text{km)}$

high shear:  $HSHEAR = 4.0 \text{ (m} \cdot \text{s}^{-1} / \text{km)}$

low momentum:  $LDWTH = 50.0 \text{ (m} \cdot \text{s}^{-1} \cdot \text{km)}$

high momentum:  $THRESH = 150.0 \text{ (m} \cdot \text{s}^{-1} \cdot \text{km)}$

## SUBROUTINE FEAT

This routine (Figure A.3) sorts vectors found by SELECT into features which could be mesocyclones, shear lines or have small size and therefore be rejected. Every vector found by SELECT during one scan of the radar is assigned to a feature, so many small features will be thrown out by subroutine CALC. Control proceeds as follows:

1. Put 1st vector into 1st feature. Initialize 1st feature's attributes.  
Mark (flag) 1st vector used.
2. CODE = 0
3. If no more vectors - go to 7      else: get next vector (we'll call it VA)
4. If VA is marked used, go to 3      else: continue
5. If no more vectors in current feature, then go to 3 ; else get  
current feature element in current feature (VB)
6. If the azimuthal center of VA is within  $2.2^\circ$  of the azimuthal center  
of VB AND the range of the 2 vectors are within 1 km
  - a) put VA in VB's feature
  - b) adjust feature attributes
  - c) mark VA used
  - d) CODE=1
  - e) Go to 3else go to 5
7. If CODE 1, go to 2 (on step 3 VA = first vector) else: continue
8. Get first unmarked vector (VA). If all vectors used, go to 11
9. Put VA in a new feature (INDEX=INDEX+1); too many features, go to 11  
Initialize feature attributes  
Go to 2 (on / VA=first vector)
10. INDEX=INDEX-1
11. END

# FEAT

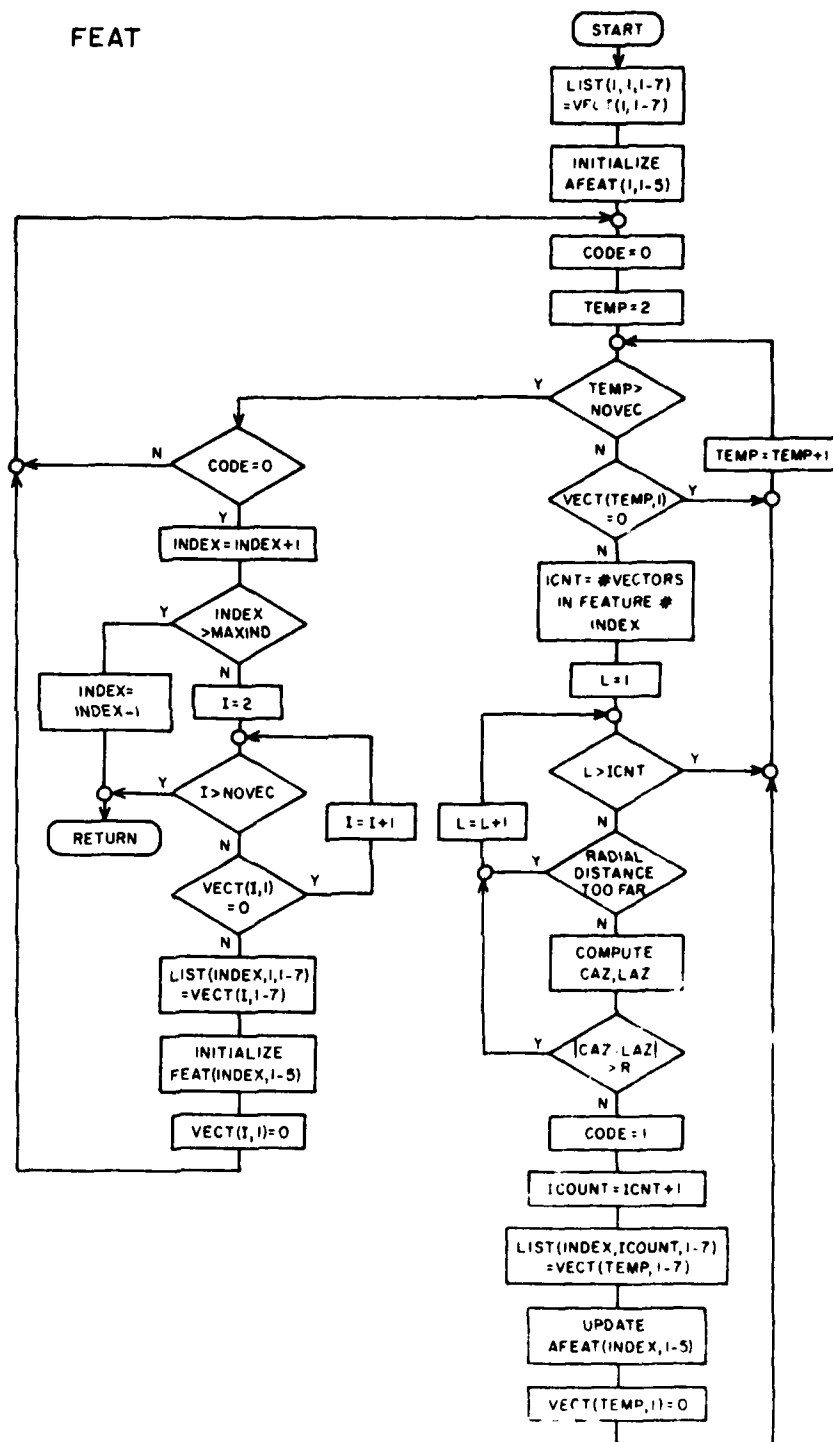


Figure A.5 Flow chart of the Subroutine FEAT.

## SUBROUTINE CALC

This routine finds important feature data used to discern which features are mesocyclones, which are shear lines, and which are neither. The control pattern below is repeated for each feature found in the last scan, using a do loop with index I (figure A.4).

1. Not enough vectors in feature - Go to 11 else: continue
2. NSUM = # vectors in feature. Zero out all sums
3. Compute sums using do loop with index J. The sums range from 1 to NSUM.

a) Vector attributes used (vectors are part of features)

R - range: LIST(I,J,1)

BAZ - beginning azimuth: LIST(I,J,2)

EAZ - ending azimuth: LIST(I,J,3)

BV - beginning velocity: LIST(I,J,4)

EV - ending velocity: LIST(I,J,5)

MO - "momentum"; here is a product of azimuthal separation ( $^{\circ}$ )  
with velocity difference: LIST(I,J,6)

SHEAR - shear =  $(EV-BV) * 180 / (DELAZ * R * \pi)$ : LIST(I,J,7)

MAZ - center azimuth =  $(EAZ-BAZ)/2+BAZ$

DELAZ - change in azimuth = EAZ - BAZ

Provision is made to account for the cases where the zero azimuth is between the beginning and ending azimuths.

b) SUMS

SUM =  $\sum MO$

SUMR =  $\sum R * MO$

SUMAZ =  $\sum MAZ * MO$

SUMSHEAR =  $\sum SHEAR$

$$AZM = \sum DELAZ \cdot MO$$

$$OAZ = \sum DELAZ$$

4. Compute data

- a)  $AVGSHR$  - average shear of feature =  $SHSUM/NSUM$
- b)  $AVGMOM$  = average momentum =  $SUM/NSUM$
- c)  $DIAMR$  - radial diameter =  $AFEAT(I,5) - AFEAT(I,4)$
- d)  $MAXSH$  - maximum shear
- e)  $MAXSP$  - maximum rotational speed =  $|EV - BV|/2$

5. If  $SUM = 0$  or  $DIAMR = 0$  or  $OAZ = 0$

go to 11

else continue

6. Compute more data

- a)  $PT$  - center of feature  $PT(I,1)$  radial =  $SUMR/SUM$   
 $PT(I,2)$  azimuthal =  $SUMAZ/SUM$

7. If  $PT(I,1) = 0$

go to 11

else continue

8. Compute more data

- a)  $DIAMAZ$  - azimuthal diameter weighted by momentum  
 $= AZM \cdot PT(I,1) \cdot \pi^2 \cdot 3 / (8 \cdot 180 \cdot SUM)$
- b)  $ODIAM$  - azimuthal diameter - unweighted  
 $= AZM \cdot PT(I,1) / (OAZ \cdot 45)$
- c)  $RATIO = DIAMAZ/DIAMR$  )  
d)  $R2 = ODIAM/DIAMR$  ) to determine symmetry
- e)  $AVGSP$  - average rotational speed =  $AVGSHR \cdot DIAMAZ/2$

9. If feature is symmetric, it is a mesocyclone ( $.5 \cdot RATIO \cdot 2$  or  $.5 \cdot R2 \cdot 2$ )  
else feature is a shear line

# CALC

COND 1 = SUM = 0 OR DIAMR = 0  
OR OAZ = 0

COND 2 = PT(1,1) = 0 OR  
PT(1,2) = 0

COND 3 = RATIO  $\leq$  0.5 OR  
RATIO  $\geq$  2.0

COND 4 = R2  $\leq$  0.5 OR  
R2  $\geq$  2.0

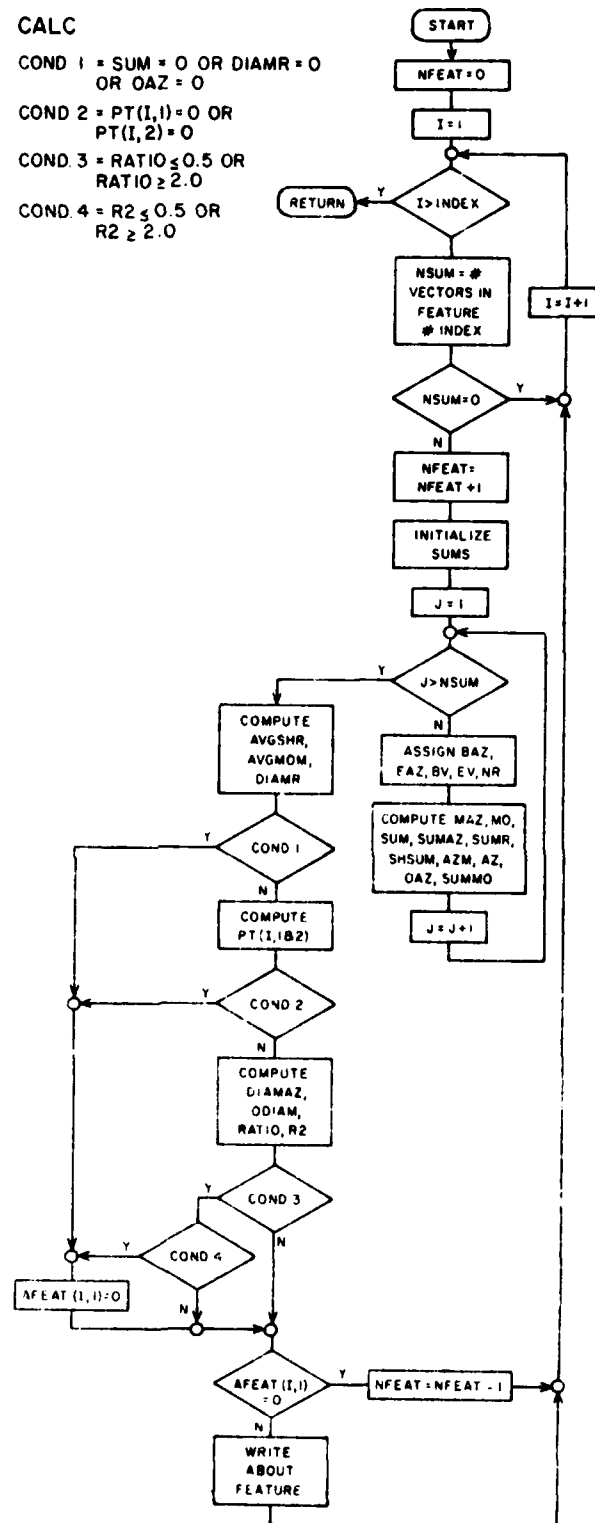


Figure A.4 Flow chart of the Subroutine CALC.

10. Write feature and its attributes
11. Stop.

#### SUBROUTINE RDREC

RDREC gets records from tape in a quasi-real time manner--one record at a time. Also the routine calls other needed preprocessing routines (Figure A.5). Control proceeds as follows:

1. If end-of-file or end-of-processing, go to 8.  
Else continue
2. Read 1 radial of raw data (CALL RWDP81)
3. Undesired radial?  
STATUS = 1, bad radial  
ITYPE  $\neq$  2, undesired type of data  
IAZMD = 2, stationary antenna (azimuthally)  
ISTAT  $\neq$  1, Cimarron data  
NTIME < IBEGT, before desired processing times  
ELEV  $\geq$  ELTH, too high for mesocyclones  
Go to 1, else continue
4. If first = 1, call PRELIM and continue, else continue
5. Expand data - CALL DPEXPAND
6. Calculate reflectivities: CALL CALREF
7. If reflectivity at any gate reflectivity threshold, then ignore velocity at that gate. Go to 9.
8. STATUS = 0 Set end-of-file indicator
9. Return



RDREC

COND 1 = STATUS  $\neq$  0 AND  
NTIME  $\leq$  IENDT  
COND 2 = STATUS = 1 OR  
ITYPE  $\neq$  2 OR IAZMD = 2  
OR ISTAT  $\neq$  1 OR  
NTIME < IBEGT OR  
ELEV  $\geq$  ELTH

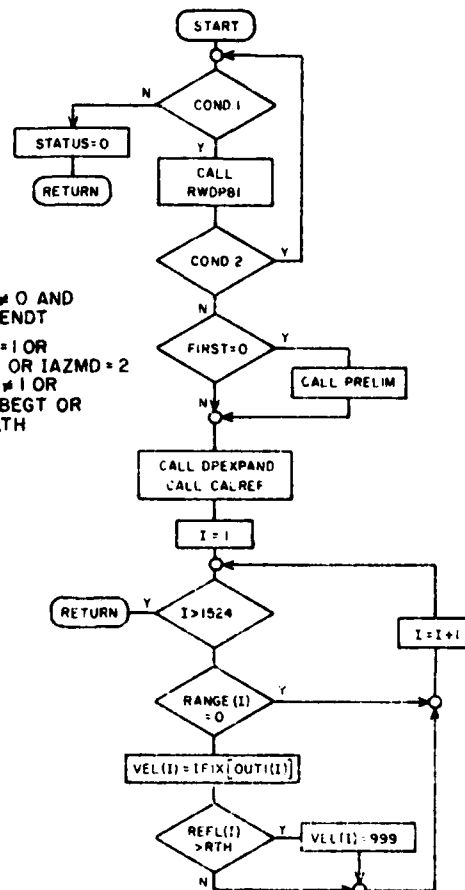


Figure A.5 Flow chart of the Subroutine RDREC.

## SUBROUTINE PRELIM

PRELIM calculates the pulse repetition time and the range to each range gate. Also the routine finds the  $\log_{10}$  of the square of the range at each range gate (Figure A.6). Control proceeds as follows:

1. Calculate BRG and DRG (call DOPRNG81)
2. a) Calculate the range at each range gate:  $R(I) = BRG + I \cdot DRG$   
b) Calculate  $\log_{10} (R(I)^2)$
3. Calculate PRT (pulse repetition time)

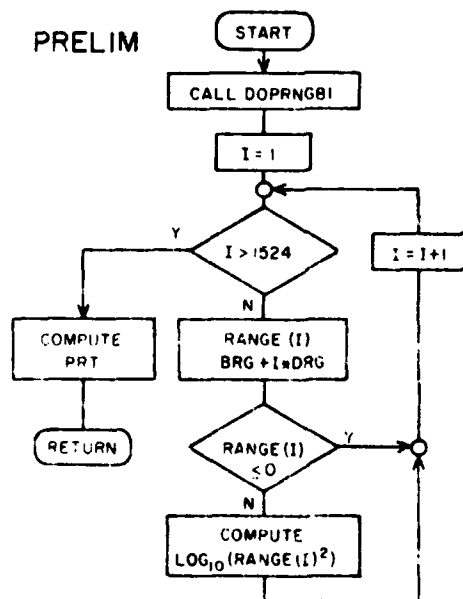


Figure A.6 Flow chart of the Subroutine PRELIM.

## SUBROUTINE UNFOLD

UNFOLD checks velocities at each range gate after the first to see if the velocity is aliased, and corrects aliased velocities (Figure A.7). The process below is repeated for the 2nd to the 1524<sup>th</sup> range gate.

1. ONE: current velocity  
OLD: velocity at preceding range gate
2. If ONE = 999 or OLD = 999 or  $R(I) \leq 0$ , go to 6
3.  $DIFONE = |ONE - OLD|$
4. If  $ONE > 0$   $VEL = ONE - 64*$   
If  $ONE < 0$   $VEL = ONE + 64*$   
If  $ONE = 0$   $VEL = 0$   
 $DIFTWO = |VEL - OLD|$
5. If  $DIFONE > DIFTWO$  current velocity = VEL
6. Stop

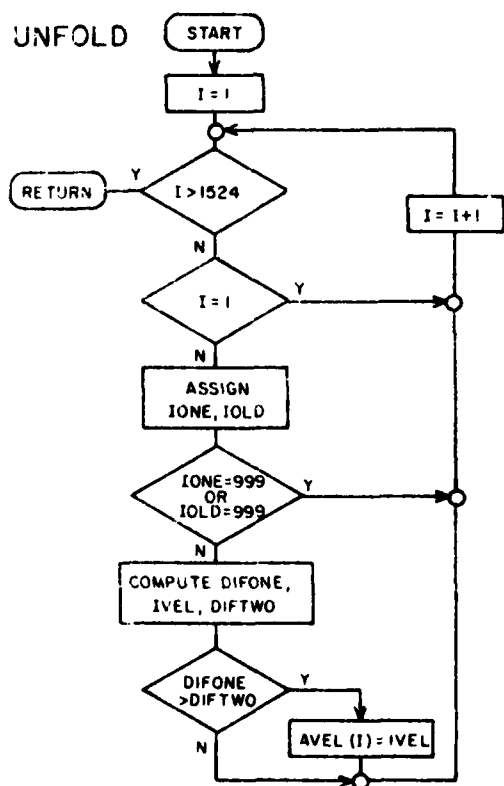


Figure A.7 Flow chart of the Subroutine UNFOLD.

\*At this point in the program VEL can have 64 digital categories that span the Nyquist interval. Depending on the actual PRT, these categories are later scaled into appropriate velocities.

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